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Meade et al.

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[45] **Date of Patent: Jun. 11, 1996**

[54] **OPTOELECTRONIC INTEGRATED CIRCUITS AND METHOD OF FABRICATING AND REDUCING LOSSES USING SAME**

[75] Inventors: **Robert Meade**, Somerville; **John Joannopoulos**, Belmont, both of Mass.; **Oscar L. Alerhand**, Marlboro, N.J.

[73] Assignee: **Massachusetts Institute of Technology**, Cambridge, Mass.

[21] Appl. No.: **280,105**

[22] Filed: **Jul. 14, 1994**

Related U.S. Application Data

[63] Continuation of Ser. No. 2,430, Jan. 8, 1993, abandoned.

[51] **Int. Cl.**^{6} **G02B 6/12**; H01L 21/70

[52] **U.S. Cl.** **385/14**; 385/15; 385/16; 385/32; 385/129; 385/131; 385/132; 385/1; 385/2; 385/43; 437/16; 437/20; 437/51

[58] **Field of Search** 385/14, 129, 130, 385/131, 132, 1, 2, 24, 32, 43; 437/15, 16, 20, 21, 51

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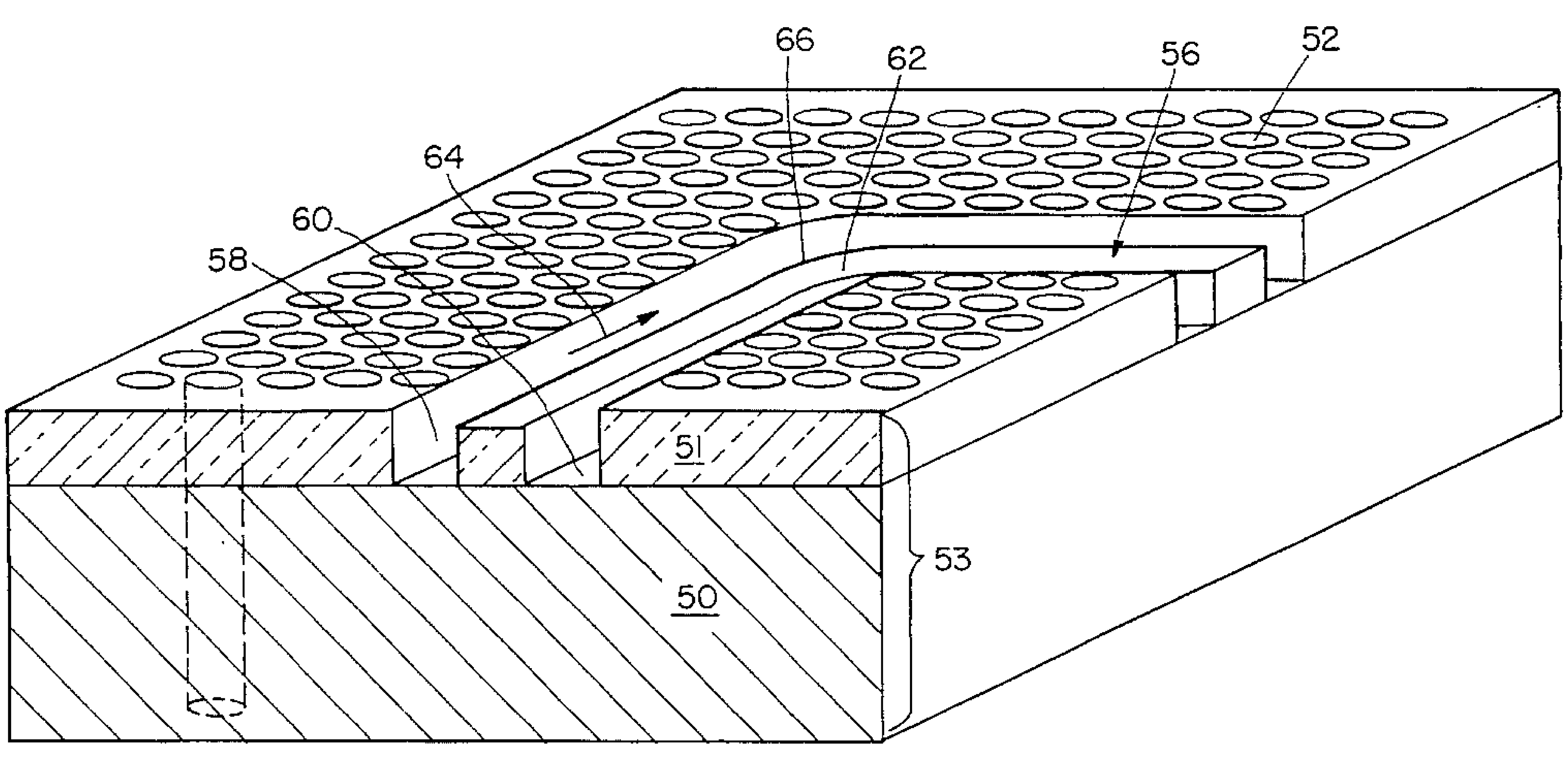
Primary Examiner—Brian Healy

Attorney, Agent, or Firm—Hamilton, Brook, Smith & Reynolds

[57] **ABSTRACT**

An optical circuit and a method for substantially eliminating radiation losses associated with optical integrated circuits and, in particular, bends in optical waveguides, is disclosed. The circuit and waveguide are fabricated on a substrate having a periodic dielectric structure. The periodic dielectric structure exhibits a range of frequencies of electromagnetic radiation which cannot propagate into the structure. The range of frequencies is known as a photonic band gap or frequency band gap. Radiation at a frequency within the frequency band gap of the structure is confined within the circuit and waveguide by the periodic dielectric structure surrounding the circuit and waveguide. Radiation losses are substantially eliminated.

62 Claims, 10 Drawing Sheets



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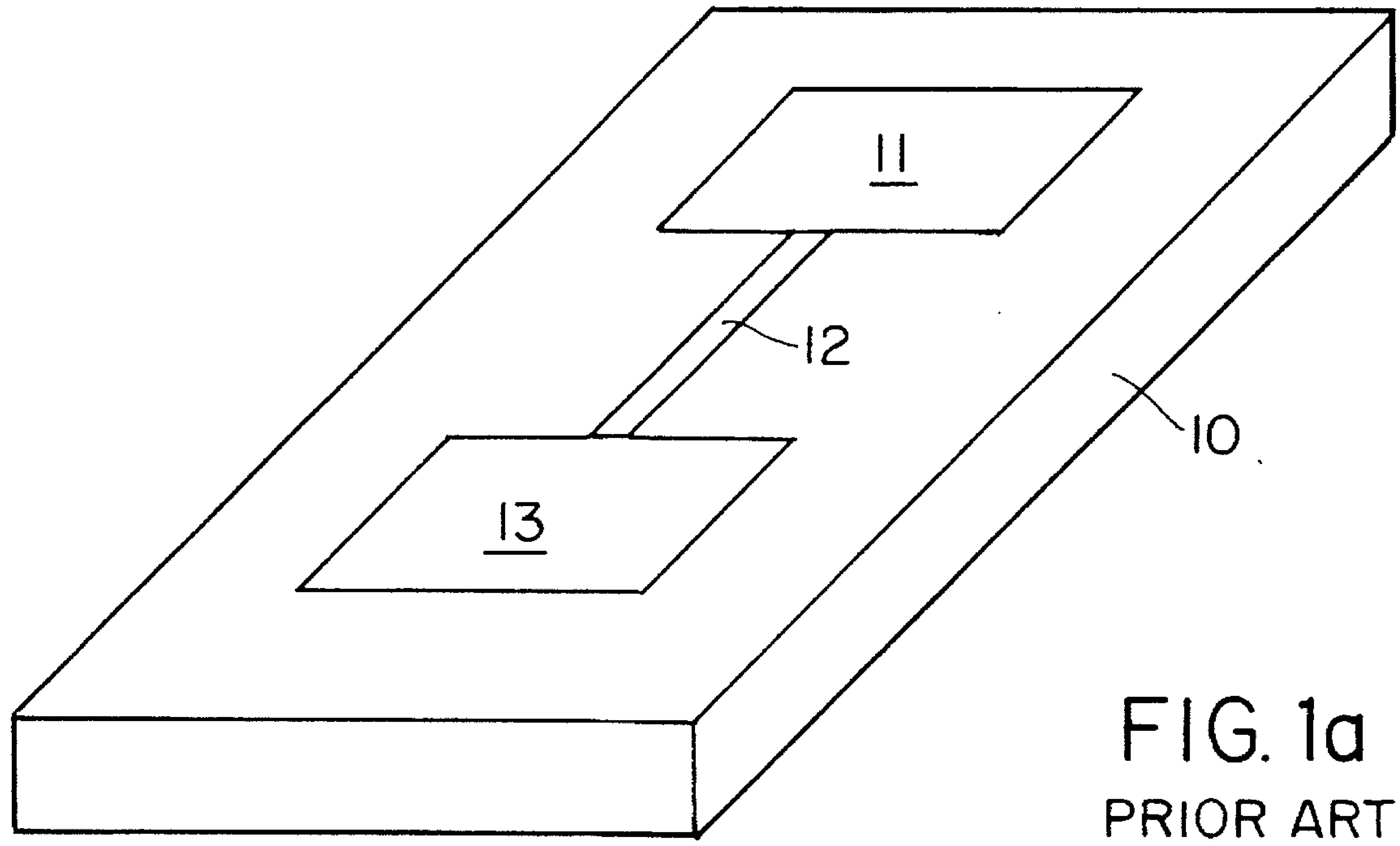

FIG. 1a
PRIOR ART

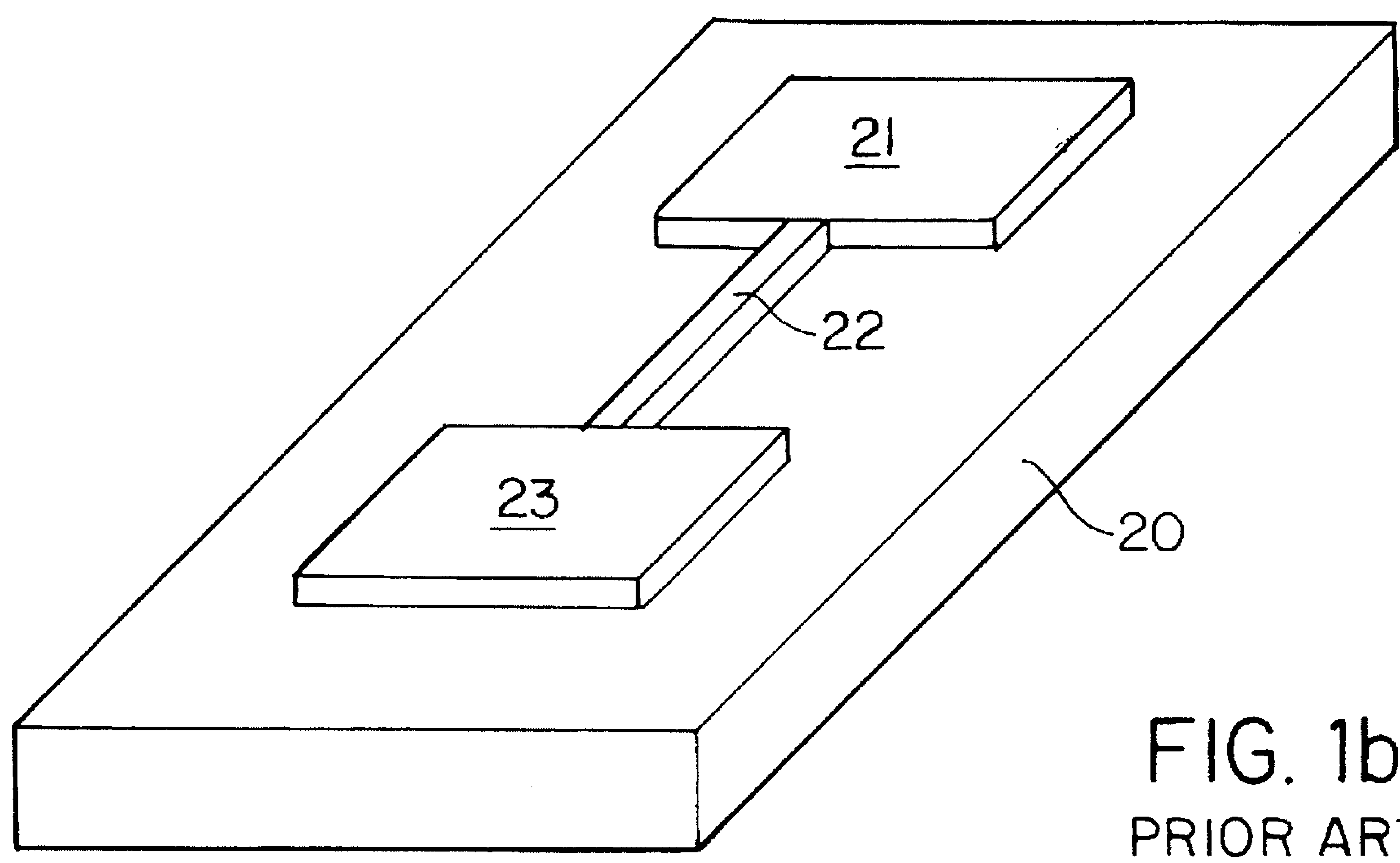

FIG. 1b
PRIOR ART

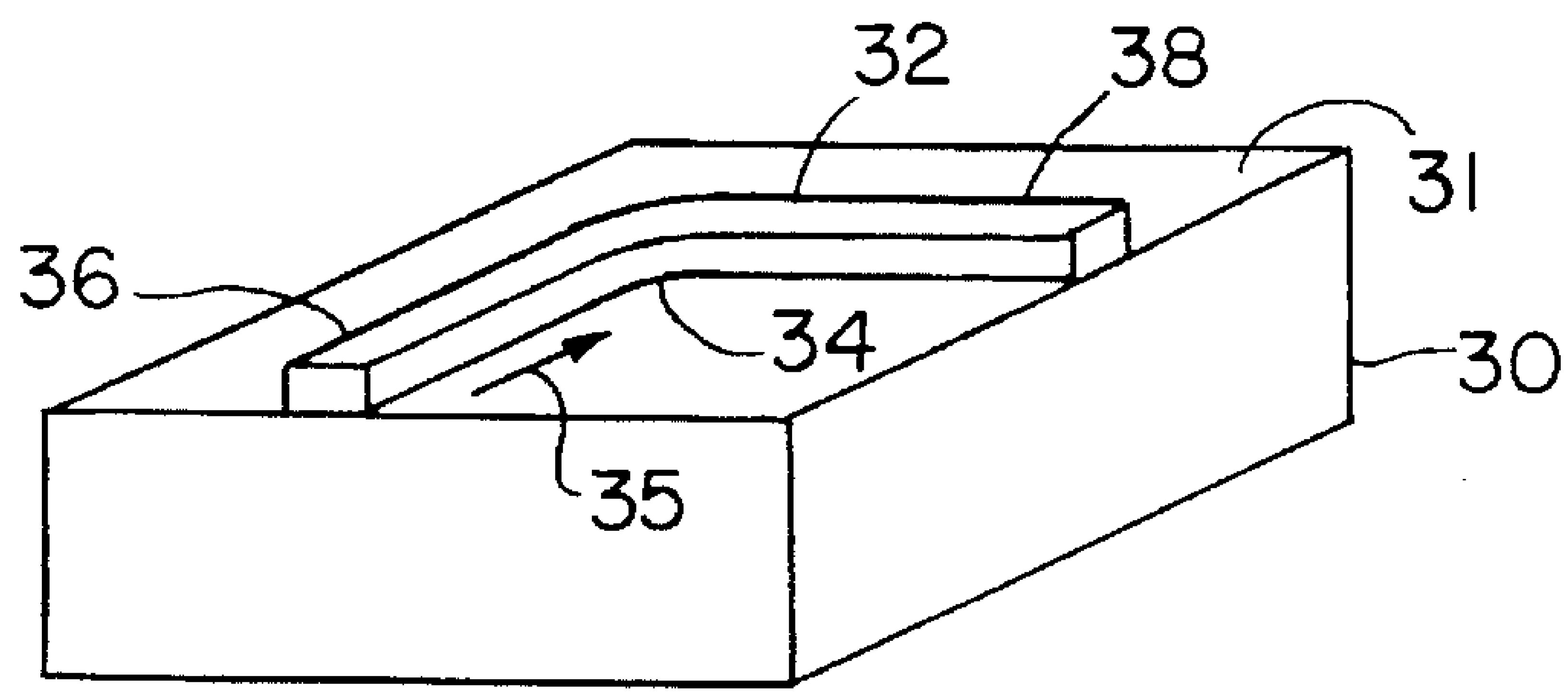

FIG. 2a
PRIOR ART

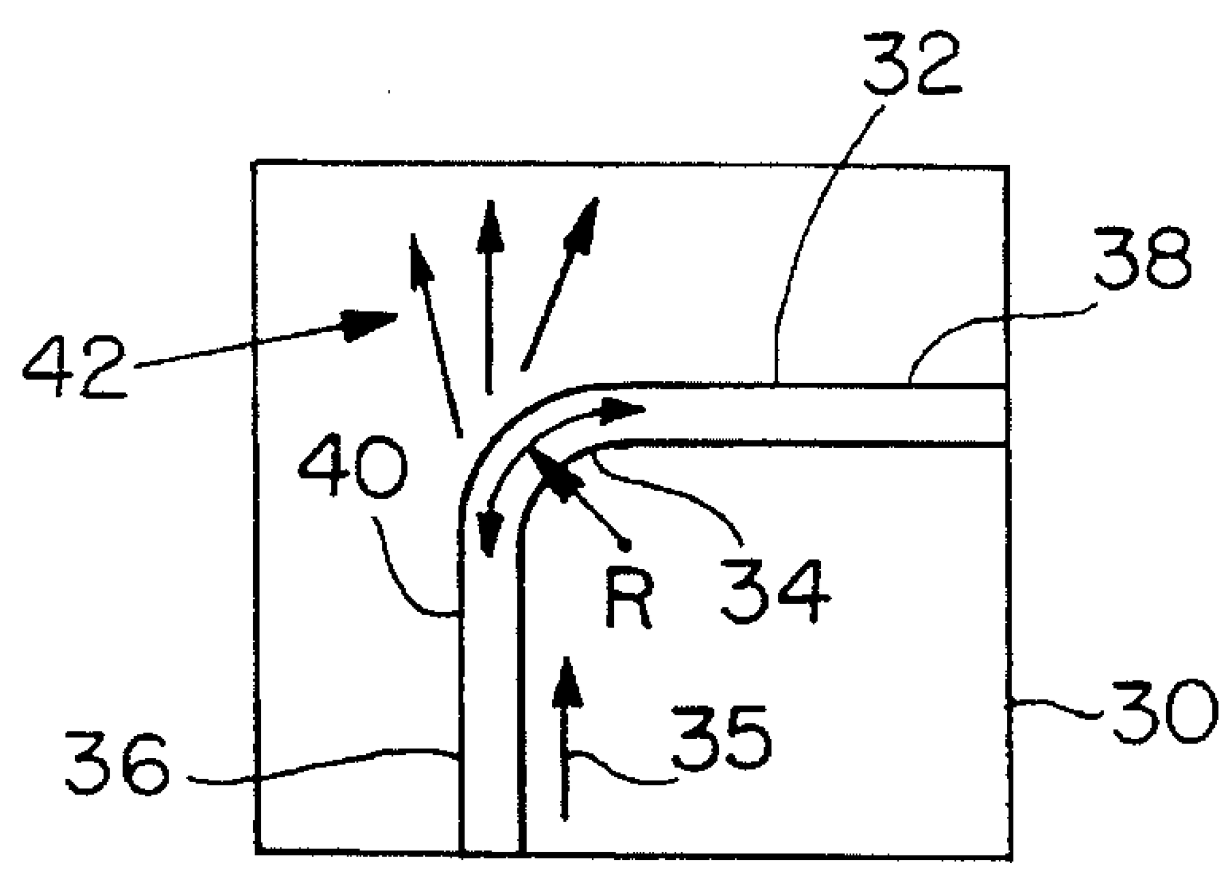

FIG. 2b
PRIOR ART

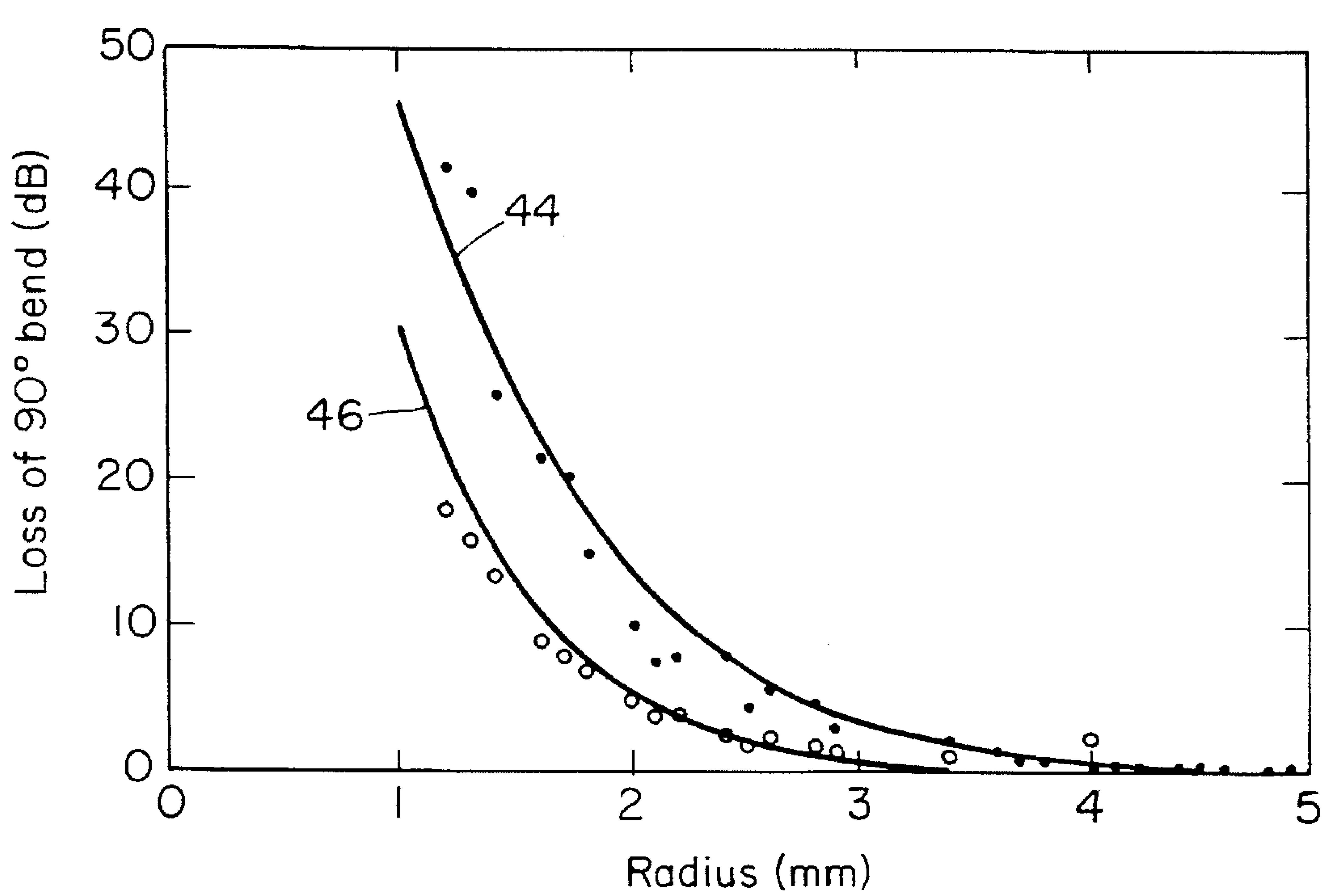

FIG. 3

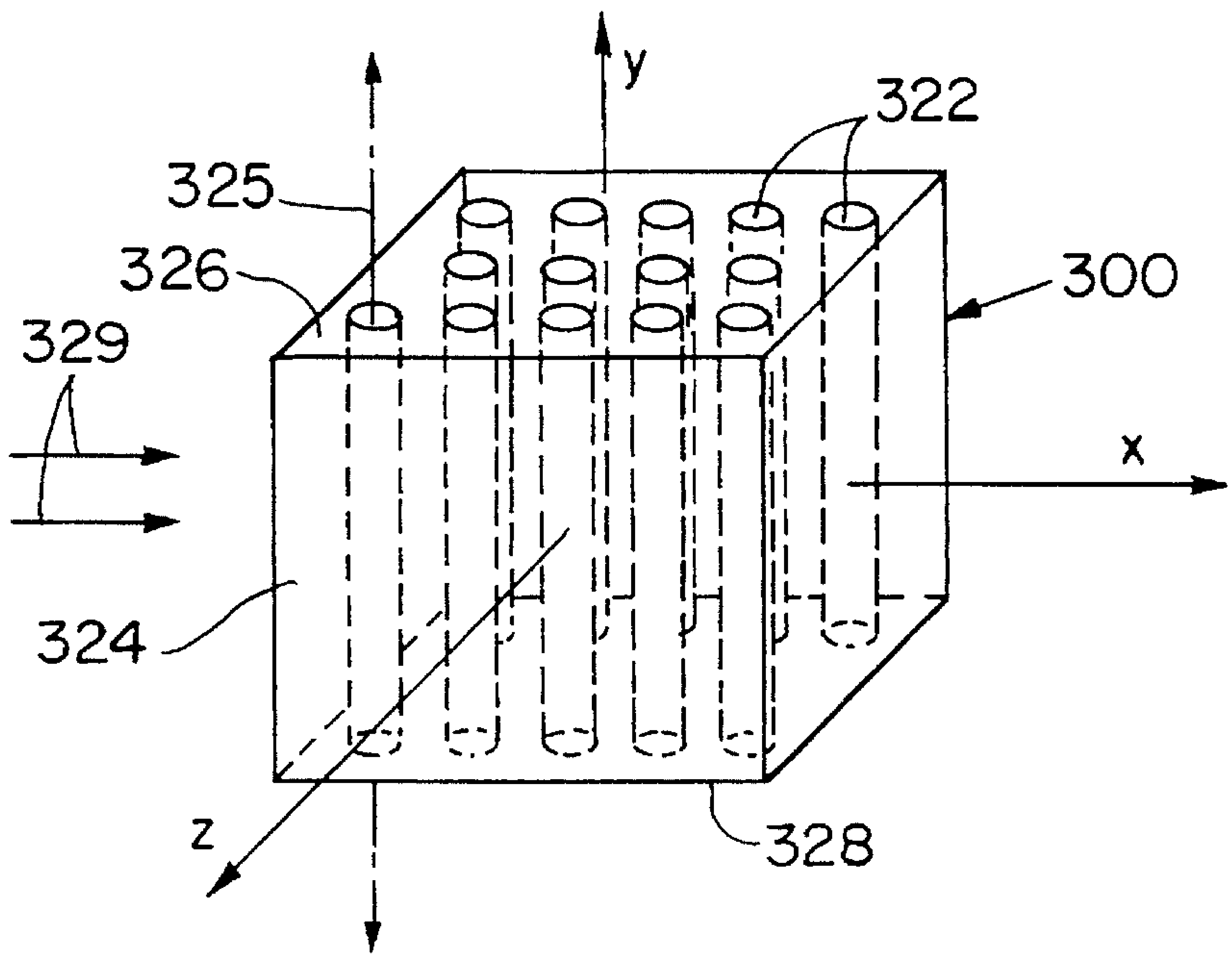

FIG. 4

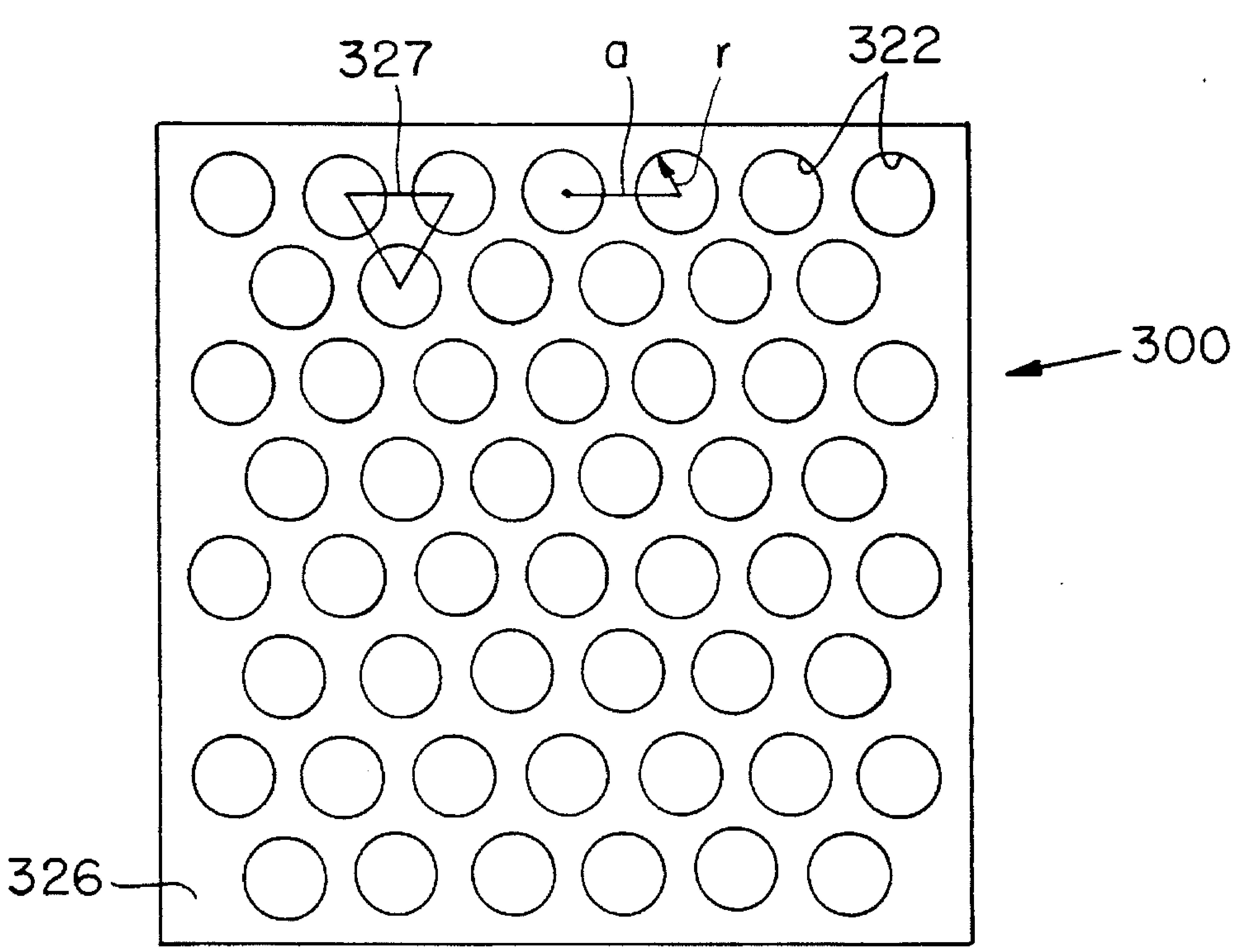

FIG. 5a

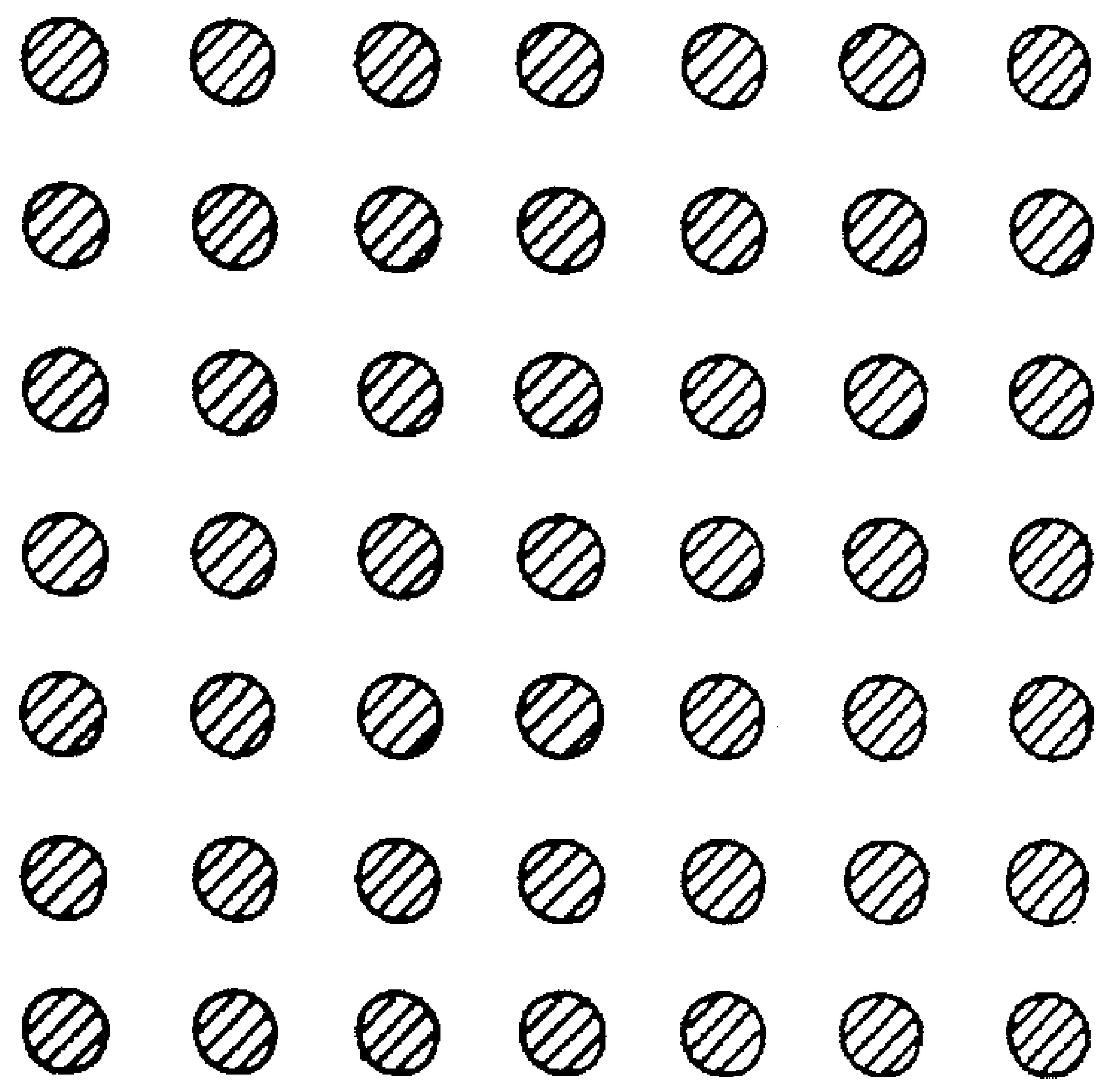

FIG. 5b

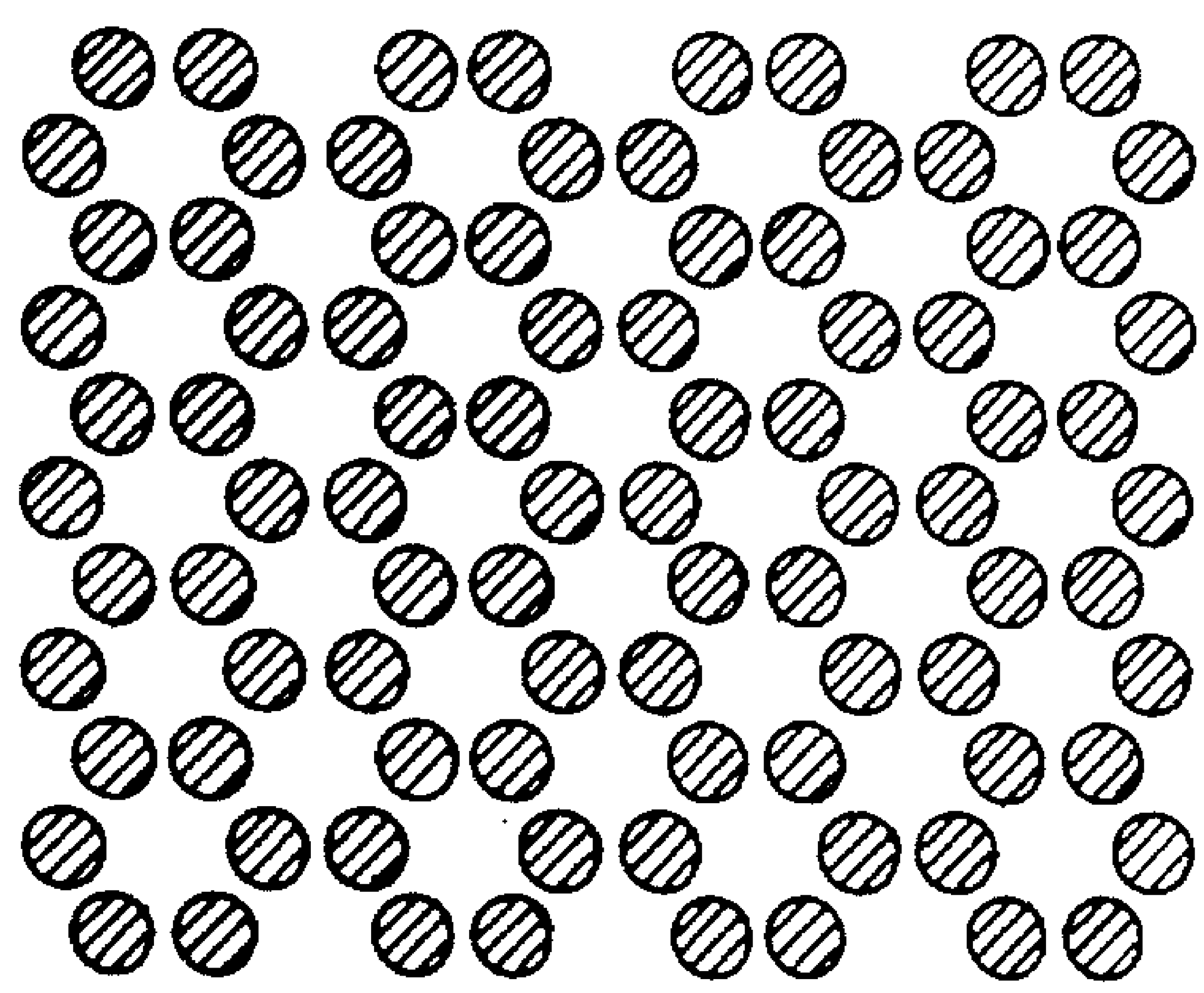

FIG. 5c

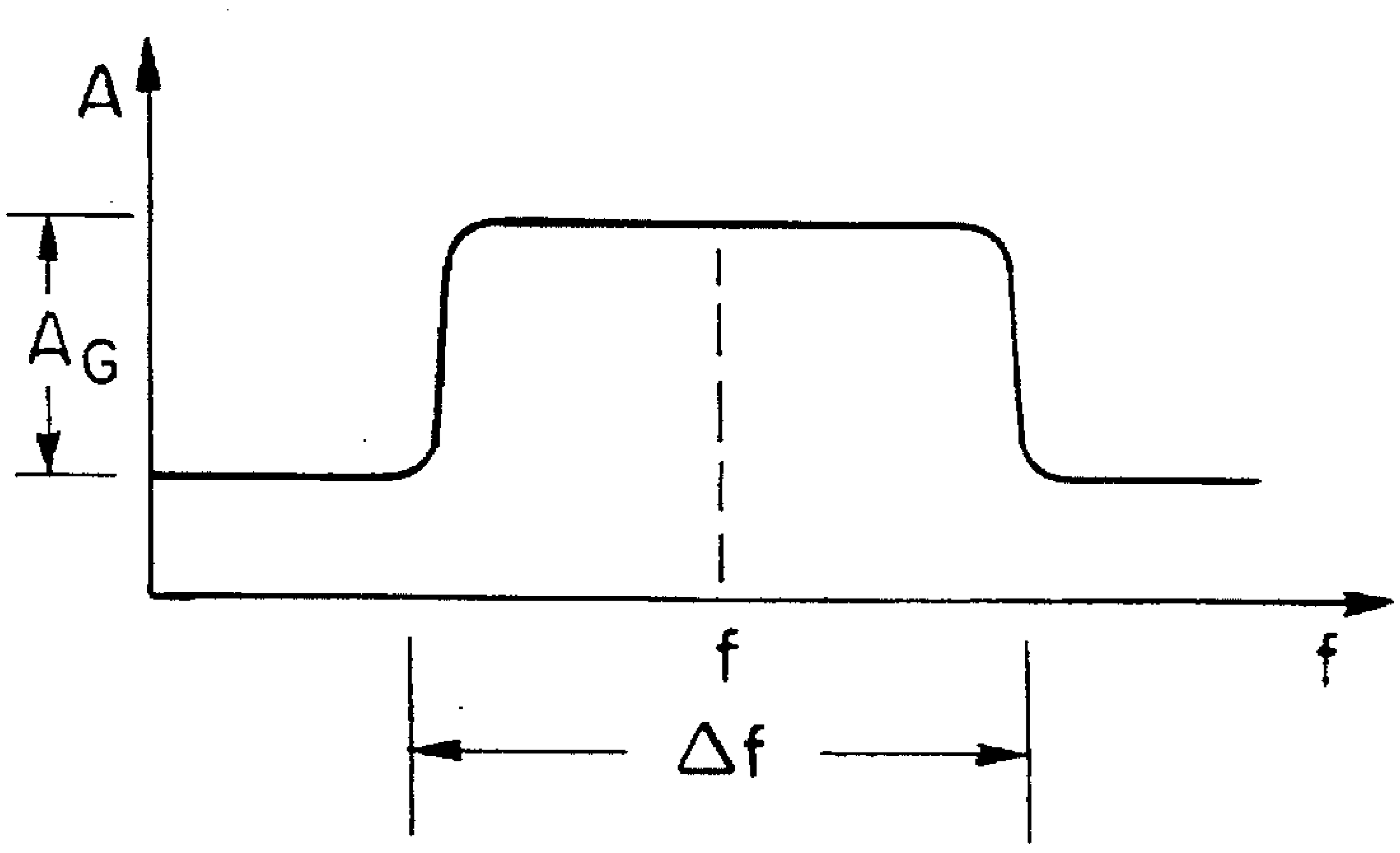

FIG. 6

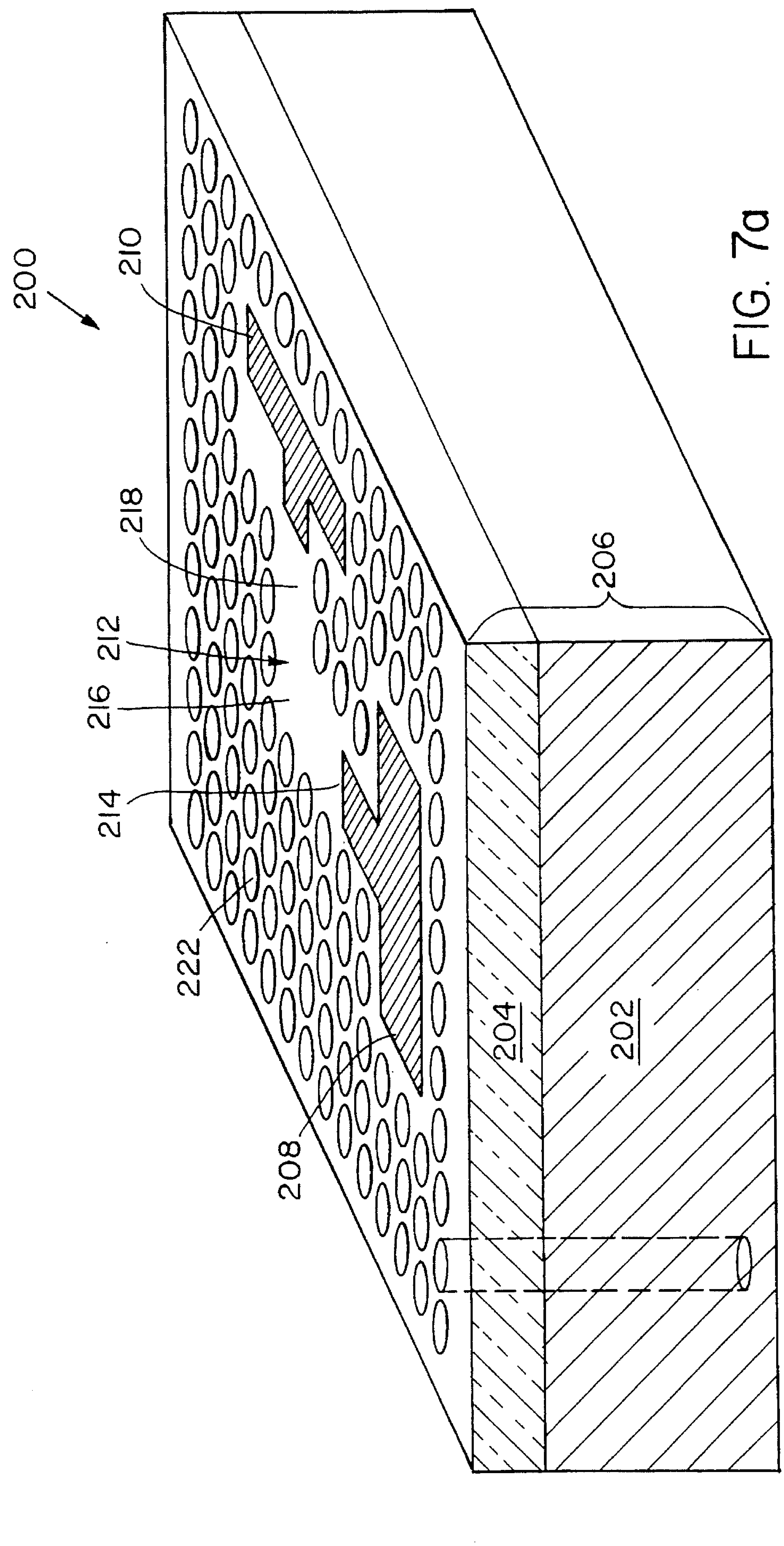

FIG. 7a

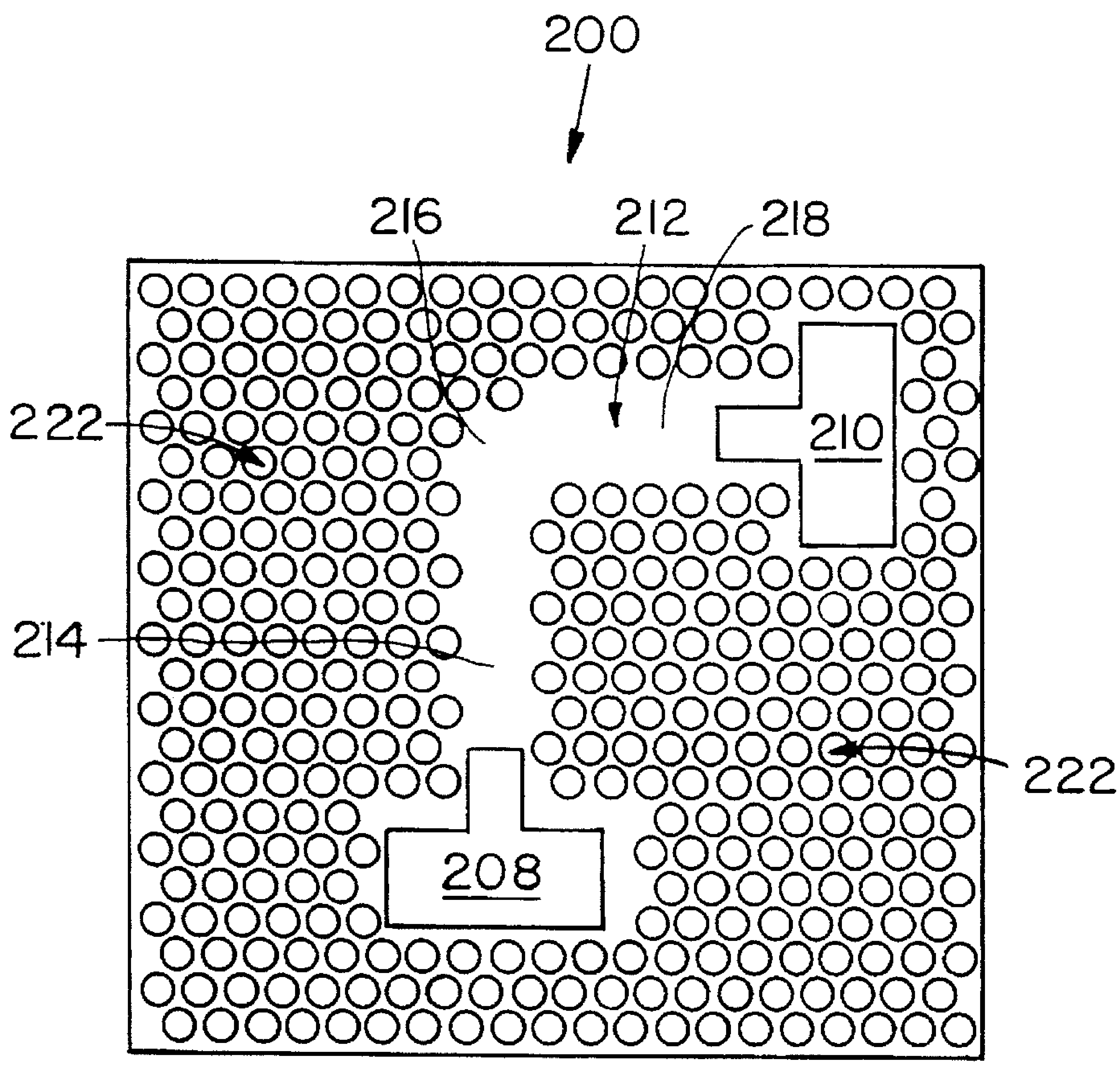

FIG. 7b

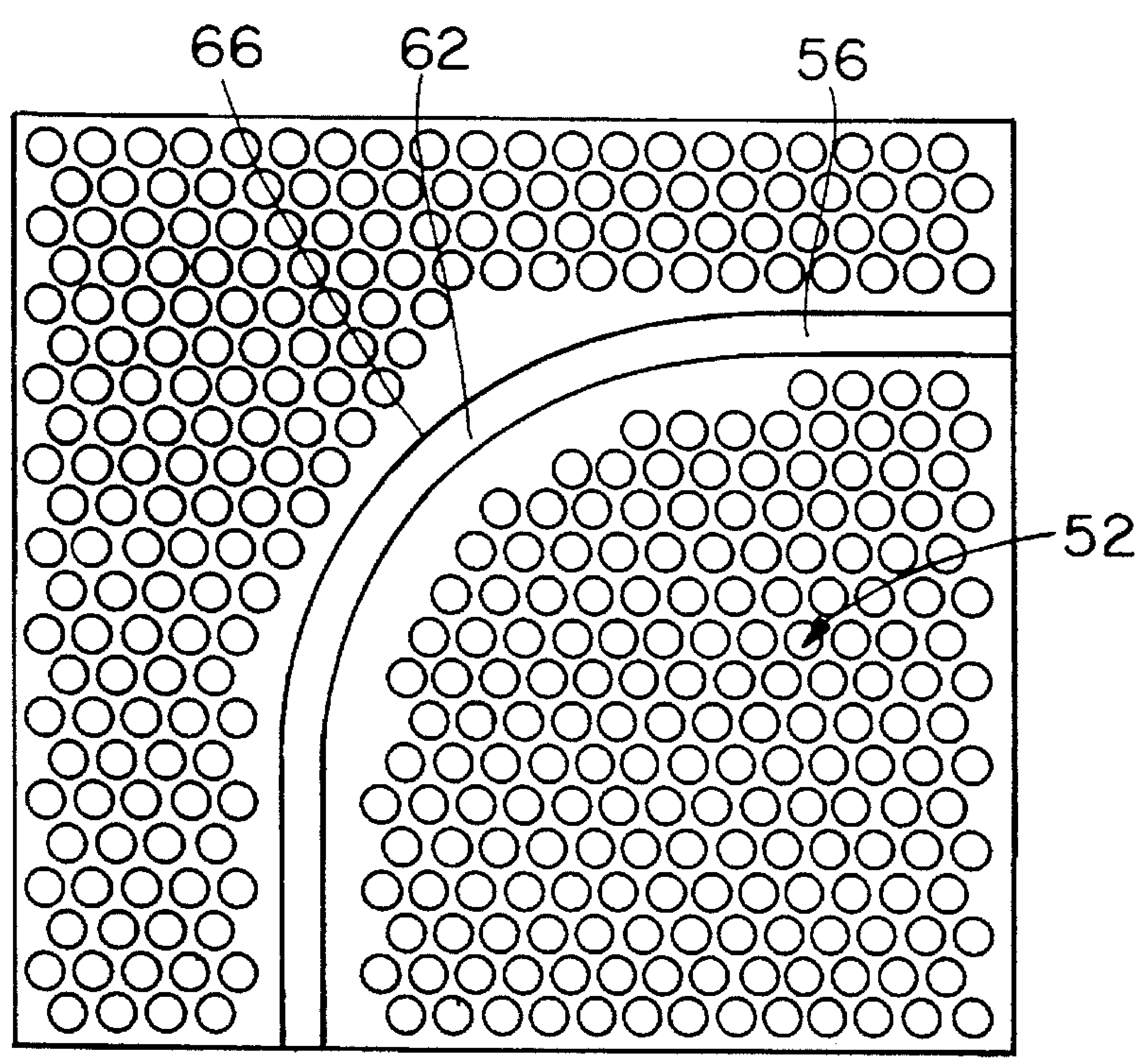

FIG. 8b

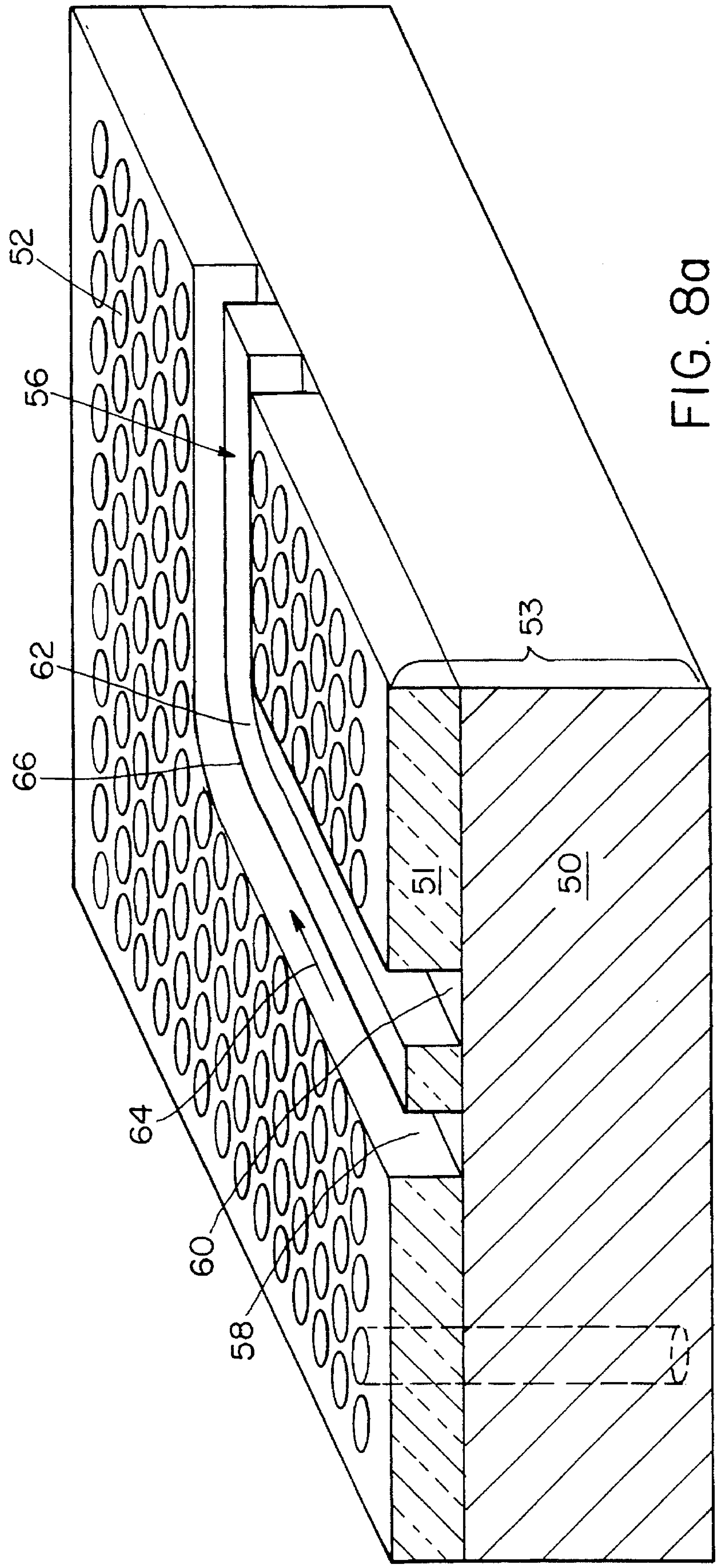

FIG. 8a

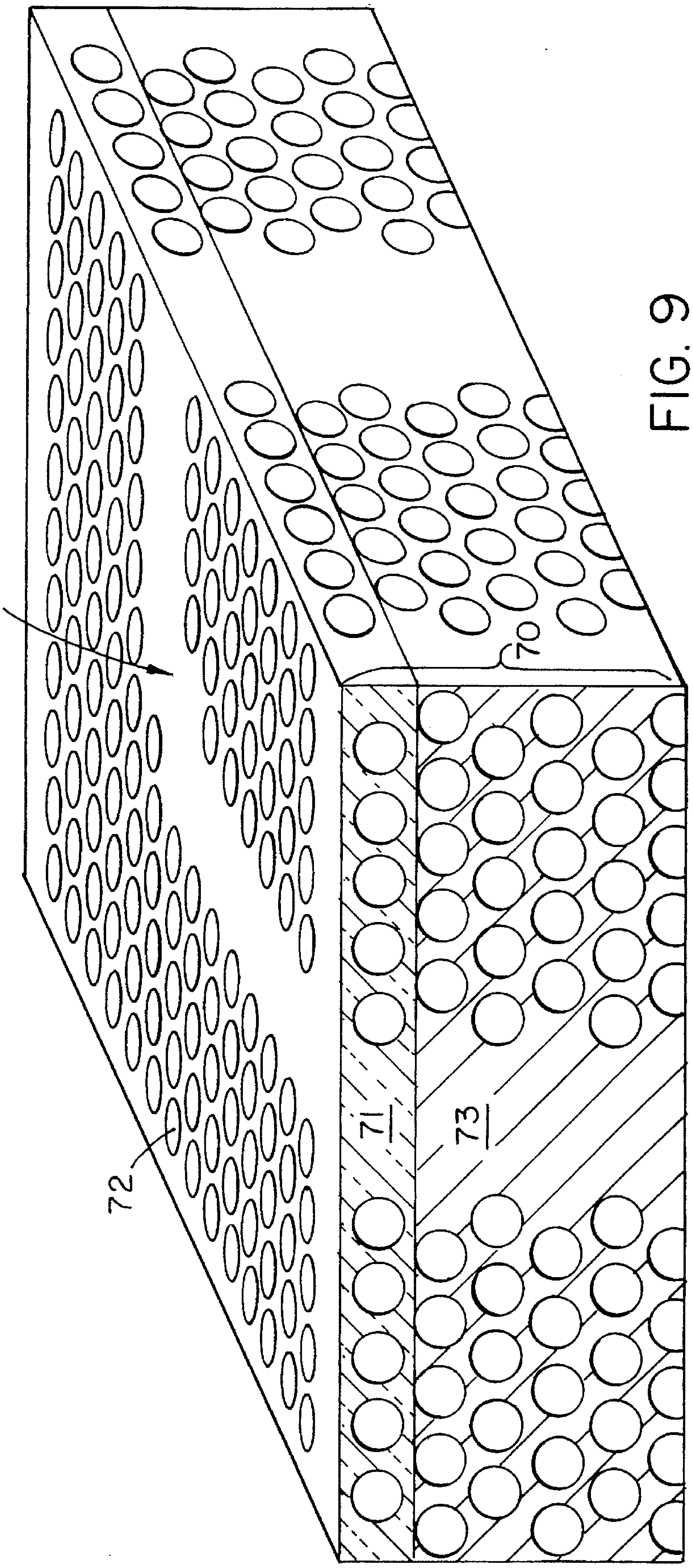

FIG. 9

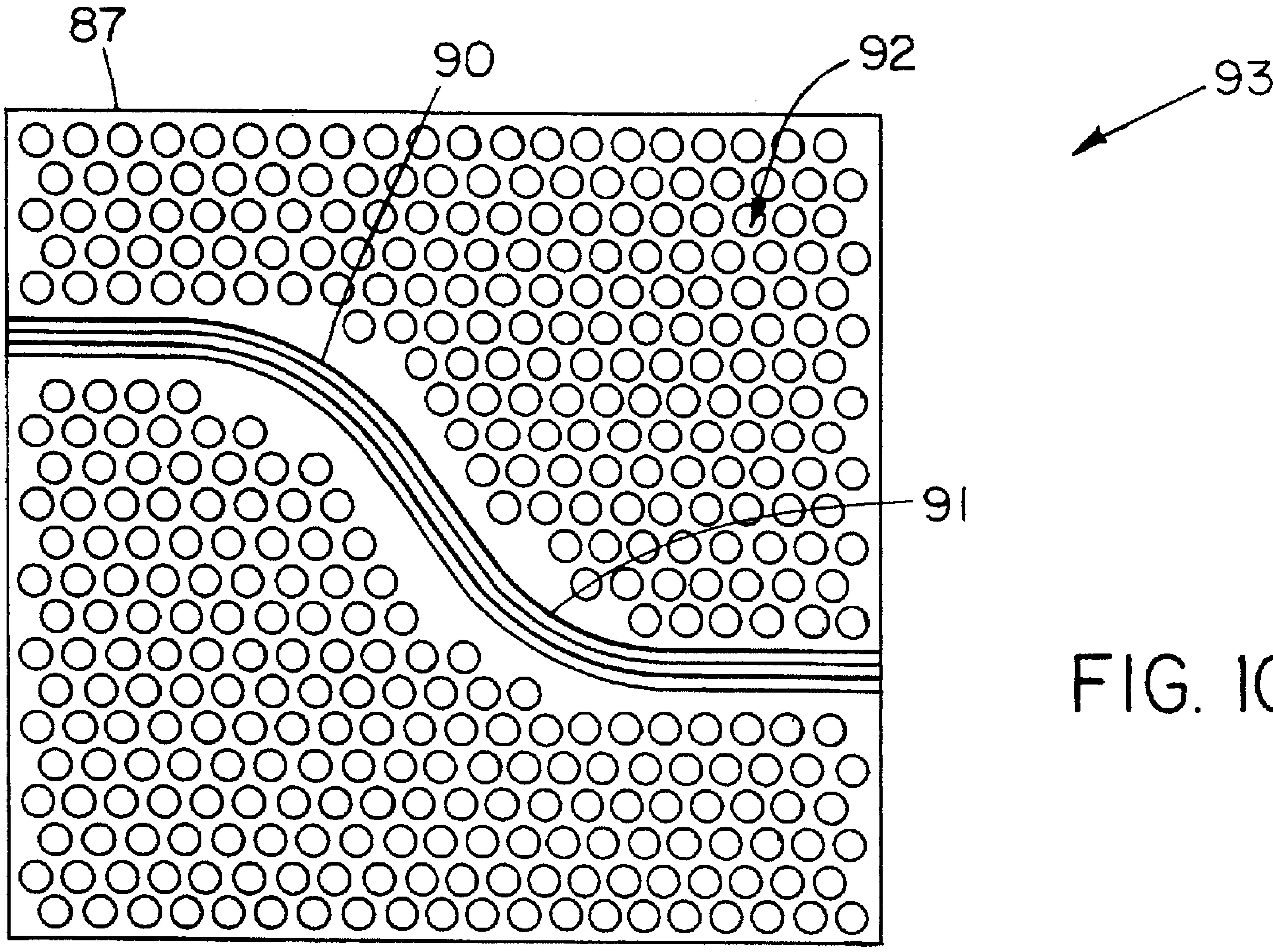

FIG. 10

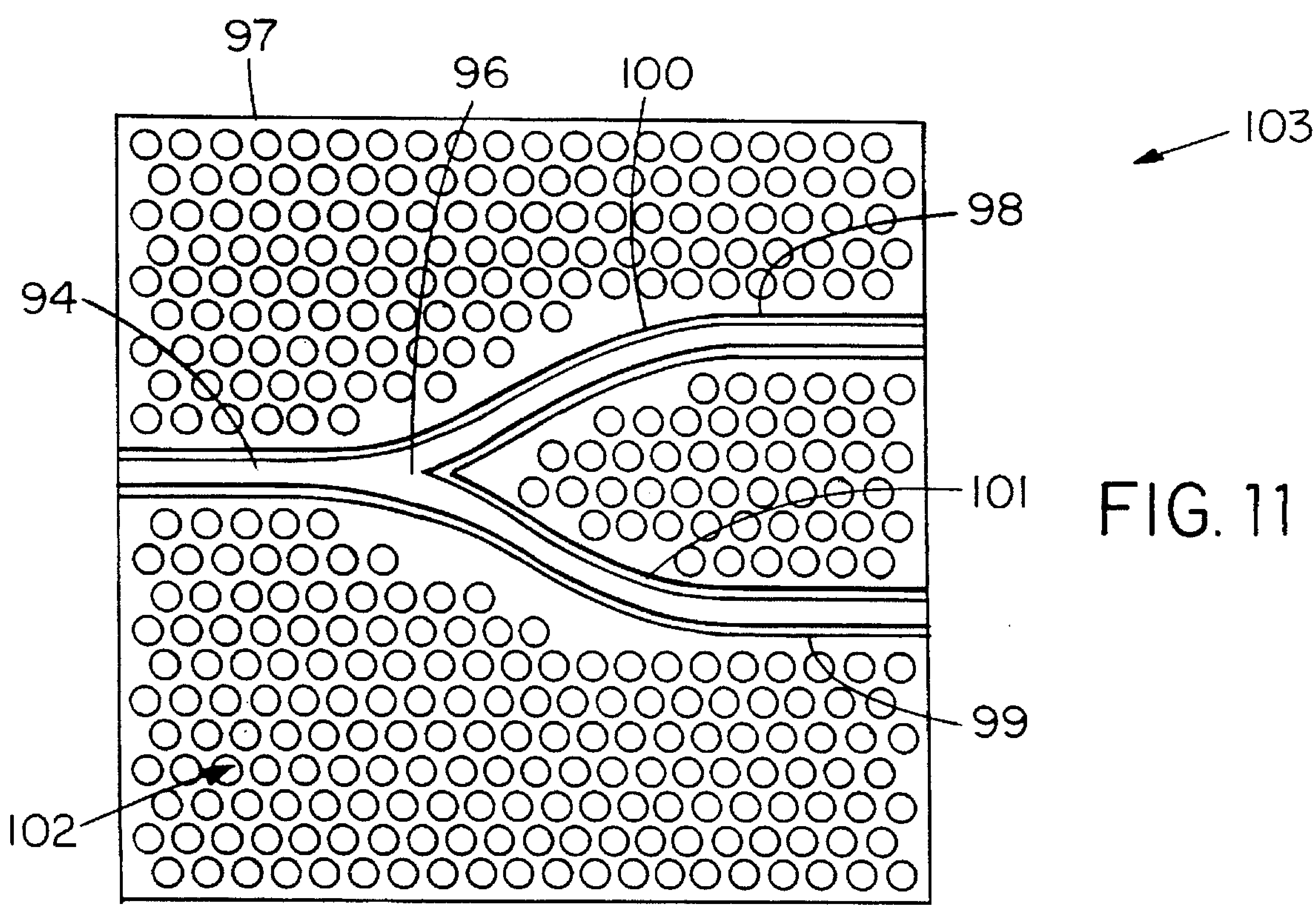

FIG. 11

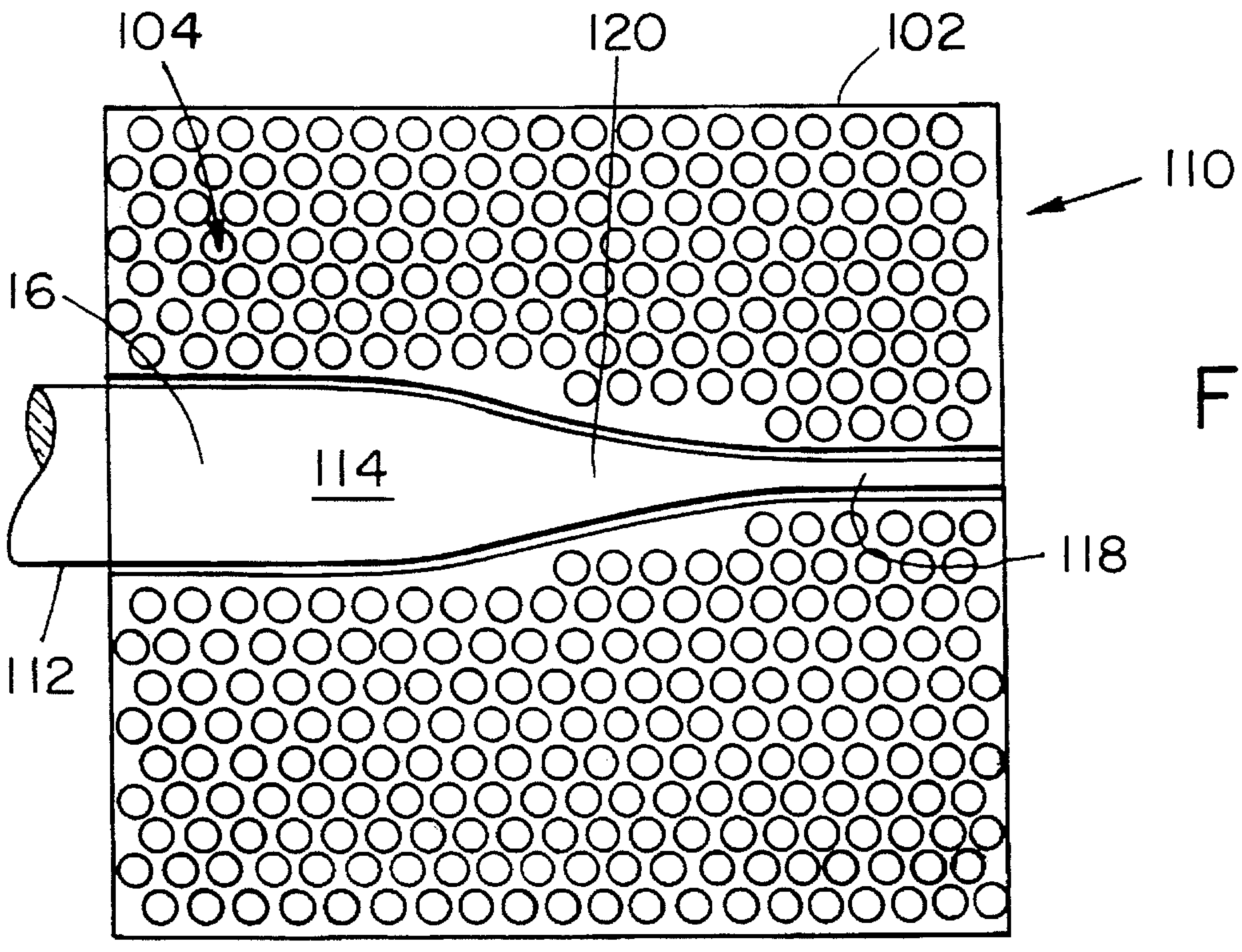

FIG. 12

OPTOELECTRONIC INTEGRATED CIRCUITS AND METHOD OF FABRICATING AND REDUCING LOSSES USING SAME

RELATED APPLICATION

This application is a continuation of application Ser. No. 08/002,430 filed on Jan. 8, 1993, now abandoned, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

Optical integrated circuits and optoelectronic integrated circuits are usually fabricated on the top surface of a uniform substrate. These circuits can experience optical losses as light propagates away from the circuits and into the uniform substrate. It is desirable to produce optical and optoelectronic integrated circuits as compact as possible on a substrate to produce small lightweight circuits. However, losses experienced by the interconnects between circuits tend to inhibit the reduction of the overall system size.

Interconnects in optical integrated circuits and optoelectronic integrated circuits are achieved by using waveguides to transport light from one optical device to another. Waveguides are also the basis of numerous optical devices including optical couplers, switches, modulators, power dividers and combiners.

Light propagating through an optical waveguide is contained within the waveguide by total internal reflection. The medium outside the waveguide has a lower index of refraction than does the interior of the waveguide. The boundary between the interior and exterior of the waveguide is characterized by a critical angle determined by the ratio of the refractive indices or index contrast of the two media. The critical angle of the boundary can be defined as the angle below which light inside the waveguide must strike the boundary in order to be reflected back into the waveguide rather than be transmitted through the boundary and out of the waveguide. Light inside the waveguide which strikes the boundary at an angle smaller than the critical angle cannot pass through the boundary and is reflected back into the waveguide.

Since nearly all of the light traveling through a straight optical waveguide strikes the waveguide boundary at very small angles, very little loss is suffered. However, in fabricating optical and optoelectronic integrated circuits, it is necessary to make optical waveguides with bends. Also, certain devices such as optical couplers require bends in their waveguides. Unlike straight waveguide sections, waveguide bends can produce significant losses. As the light traveling through the waveguide enters a bend, it strikes the boundary at a larger angle than it does in a straight section. If the index contrast does not provide a large enough critical angle, some of the light escapes from the waveguide, thus introducing bend loss.

Bend losses have proven to be a substantial impediment to the development of optical and optoelectronic integrated circuits. To minimize losses, bends must be made with large radii of curvature, typically on the order of 10 mm. Such large bend radii are not practical for compact optical and optoelectronic integrated circuits.

Numerous approaches have been suggested to minimize bend losses. One of these is the use of abrupt bends rather than curved bends. Abrupt bends have sharp corners joining two straight sections of waveguide. The drawback to abrupt bends is that the bend angle must be very small, on the order of 1 degree. So, this approach contributes little to making circuits more compact.

Another approach has been to grade the index of refraction of the substrate in the area of the bend to maintain internal reflection around the bend. Combinations of these two approaches have also been suggested. However, no present approach appears to be able to substantially reduce the radii of curvature of waveguide bends to facilitate the development of compact optical and optoelectronic integrated circuits.

SUMMARY OF THE INVENTION

The present invention is an optical circuit and a method which substantially eliminates radiation losses in optical integrated circuits. The circuit is formed on a surface of a substrate made of a semiconductor or other type material including dielectric and optical materials. The substrate comprises a region which is characterized by a frequency band gap. The frequency band gap is a band of frequencies at which electromagnetic radiation and, in particular, light waves cannot propagate through the region. The circuit is formed in the region having the frequency band gap such that radiation which would otherwise escape from the circuit into the substrate cannot propagate into the substrate.

The circuit of the present invention experiences reduced radiation losses at frequencies within the band gap of the substrate. In particular, losses at waveguide bends are substantially eliminated. Some of the light traveling through a waveguide bend strikes the boundary between the interior and the exterior of the waveguide at angles greater than the critical angle and would otherwise tend to escape from the waveguide into the substrate. However, in the present invention, the bend is formed in the region of the substrate with the frequency band gap. Light at a frequency within the band gap cannot propagate into the substrate. The light is confined within the optical circuit and the waveguide.

The region of the substrate with the frequency band gap has a periodic dielectric structure. A periodic dielectric structure is a structure which exhibits a periodic spatial variation in dielectric constant. As applicable to the present invention, the variation in dielectric constant may be periodic in either two-dimensional or three-dimensional space within the structure.

There are various methods of forming such structures. One of these methods involves forming a periodic pattern of holes in a uniform substrate material. Another is removing substrate material such that what remains is a periodic pattern of cylindrical or other similarly shaped rods of substrate material.

There are also various methods of forming an optical waveguide on the substrate. In one embodiment, an epilayer of material of high refractive index is formed on top of a substrate having a lower index. Next, the periodic dielectric structure is formed on opposite sites of a channel in the epilayer of uniform material. The channel is shaped as desired to serve as the waveguide. The periodic dielectric structure on either side of the channel prevents radiation into the substrate. Thus light is guided through the channel by the periodic dielectric structure. Light is confined vertically within the channel by internal reflection due to the index contrast between the waveguide in the epilayer and the air on top and between the waveguide and the substrate on the bottom. In other embodiments, a material having a higher index of refraction than the substrate may be diffused into the substrate or etched on the substrate. Alternatively, a material of higher refractive index may be deposited by sputtering, evaporation or other process onto the surface of the substrate. Another method involves forming a pair of trenches in a high-refractive-index layer deposited on the top surface of the substrate. The material between the trenches serves as the optical waveguide. The air in the trenches is the low-refractive-index exterior medium which provides lateral internal reflection due to index contrast. Periodic dielectric structure is provided on the outside of the trenches to eliminate loss where the requirements for internal reflection are not met. Vertical losses are eliminated by internal reflection due to the refractive index contrast.

The present invention provides substantial advantages over previous methods of reducing loss in optical circuits and in optical waveguide bends. Unlike previous approaches, it is the substrate itself which prevents radiation from escaping into the substrate. The present invention does not rely upon physical constraints of a waveguide such as the bend angle, as in the abrupt bend approach. In the present invention, the waveguide bend radius can be arbitrarily small because it is the substrate which is preventing loss. Also, the index grading approach relied on the index contrast between the waveguide and the substrate to maintain internal reflection. Even with index grading, a critical angle is present which constrains the radius of curvature. Because the present invention does not rely solely on index contrast and internal reflection at bends, the radius of curvature at the bend is not so constrained.

Because waveguide bend radii are reduced, optical and optoelectronic circuits can be made much more compact and light weight. These circuits can be totally integrated. Different optical devices and interconnects can be fabricated on a common substrate. High-speed electronics can be fabricated on the same chip as associated optoelectronic devices.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

FIG. **1***a* is a schematic perspective view of a prior art optical circuit.

FIG. **1***b* is a schematic perspective view of another prior art optical circuit.

FIG. **2***a* is a schematic perspective view of a prior art uniform substrate with a rib waveguide section having a bend.

FIG. **2***b* is a schematic top view of the waveguide section of FIG. **2***a*.

FIG. **3** is a graph of the loss associated with a 90° circular waveguide bend versus the radius of curvature of the bend for two propagation modes.

FIG. **4** is a schematic perspective view of a periodic dielectric structure having two-dimensional periodicity.

FIG. **5***a* is a schematic top view of the periodic dielectric structure of FIG. **4** showing a triangular lattice pattern.

FIG. **5***b* is a schematic top view of a periodic dielectric structure showing a square lattice pattern.

FIG. **5***c* is a schematic top view of a periodic dielectric structure showing a hexagonal lattice pattern.

FIG. **6** is a graph of the wave attenuation in the band gap versus frequency of the wave.

FIG. **7***a* is a schematic perspective view of an optical circuit in accordance with the present invention.

FIG. **7***b* is a schematic top view of the optical circuit of FIG. **7***a*.

FIG. **8***a* is a schematic perspective view of a waveguide section on a substrate having a two-dimensional periodic dielectric structure in accordance with the present invention.

FIG. **8***b* is a schematic top view of the device of FIG. **8***a*.

FIG. **9** is a schematic perspective view of a waveguide on a substrate having a three-dimensional periodic dielectric structure in accordance with the present invention.

FIG. **10** is a schematic top view of an S-bend in accordance with the present invention.

FIG. **11** is a schematic top view of a Y-coupler in accordance with the present invention.

FIG. **12** is a schematic top view of a waveguide taper in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Optical integrated circuits and optoelectronic integrated circuits can be classified as either active or passive circuits. Optical integrated circuits perform a variety of passive functions, including switching and modulating, without generating or detecting light. Optoelectronic circuits generate and detect light as well as perform certain passive functions. The present invention is applicable to both types of circuits.

It should be noted that throughout this application, the terms "optical integrated circuits", "optoelectronic circuits", "optical circuits", and other related terms will be used to describe the various types of circuits to which the invention is applicable. Unless otherwise specifically stated, the use of one of these terms in this application does not limit the applicability of the description to that type of circuit. One term is selected over another for illustration purposes only. The present invention is applicable to all of these circuits.

Optical circuits can be fabricated on a top surface of a substrate. The optical waveguides which connect the circuits can also be fabricated on the surface of the substrate. These optical waveguides consist of a channel having an index of refraction which is higher than the index of refraction of the surrounding substrate. Because of the index contrast, light is guided along the channel by total internal reflection.

Optical waveguides are used to guide optical signals among the elements in optical and optoelectronic integrated circuits and are analogous to the metallic lines used to guide electrical signals among electronic integrated circuits. They connect external optical devices such as fiber optic cables with internal optical devices such as switches, modulators, sources, and detectors. In addition, they form the basic structural elements in numerous optical devices including optical couplers, switches, modulators, power dividers, and combiners.

Integrated optical circuits and waveguides can be implemented by several different techniques. One prior art example is shown in FIG. **1***a*. A substrate **10** is made of a material such as $LiNbO_3$ having a low index of refraction. Optical circuits **11** and **13** are formed in the substrate **10** by techniques such as photolithography, diffusion, ion implantation, etching and the like. The optical waveguide **12** is made of a material having a high index of refraction which may be formed by diffusing titanium into the substrate **10**.

Another type of integrated optical circuit and waveguide, commonly referred to as a rib waveguide, is shown in FIG. **1**b. The rib waveguide **22** connects circuits **21** and **23**. In this device, the optical channel **22** of high refractive index is formed on the top surface of a low-refractive-index semiconductor substrate **20**. The substrate material may be $Ga_xAl_{(1-x)}As$ or other similar material. The channel **22** may be formed of GaAs or other high-refractive-index material. The channel **22** is formed by depositing GaAs onto the surface of the substrate **20**.

FIGS. **1**a and **1**b illustrate straight waveguide sections **12** and **22**. Light propagating through the waveguides strikes the barrier between the interior and exterior of the waveguides at small angles. Consequently, the light is confined within the waveguides by total internal reflection. However, to be useful in optical integrated circuits applications, waveguides, at times, must include bends.

FIG. **2**a schematically depicts a section of a prior art rib waveguide **32** which includes a 90° circular bend **34**. The waveguide **32** is fabricated on the top surface **31** of a substrate **30** as described above in connection with FIG. **1**b. FIG. **2**b is a schematic top view of the waveguide section **32**.

For purposes of illustration, light is assumed to propagate through the waveguide **32** in the direction indicated by arrows **35**. It will be understood that the actual direction of propagation is immaterial to the invention. The light travels through straight section **36** of the waveguide **32** and then enters bend **34**. The light which remains within the waveguide after passing through the bend travels through straight section **38**.

As light leaves the straight section **36** and enters the bend **34**, it strikes the barrier **40** between the interior and the exterior of the waveguide at larger angles. Some of these angles exceed the critical angle required for reflection determined by the index contrast at the barrier **40**. The light which exceeds the critical angle passes through the barrier **40**, exits the waveguide **32**, and propagates into the air around the waveguide and the substrate **30**. This lost light, represented by arrows **42** in FIG. **2**b, is the optical loss associated with the bend, or simply the bend loss.

As shown in FIG. **2**b, the bend **34** has a radius of curvature R. As R decreases, the angle at which light strikes the barrier **40** increases. More light escapes from the waveguide **32** causing increased bend loss. Experiments have shown that bend losses increase exponentially with decreasing bend radius of curvature That is $L \sim ae^{-R/b}$, where L is the loss, R is the radius of curvature, and a and b are constants.

Depending upon the application in which the waveguide is used, there is a certain maximum bend loss which can be tolerated. This maximum tolerable bend loss corresponds to a minimum allowable bend radius. Thus, bend loss imposes a restraint on the ability to reduce the size of the waveguide bend, and, consequently, on the ability to fabricate compact optical integrated circuits.

FIG. **3** is a graph of experimental data which depicts a relationship between the radius of curvature of a 90° circular waveguide bend and the loss associated with that bend. Bend loss in decibels (dB) is plotted as a function of radius of curvature in millimeters (mm) for two modes of propagation. Curve **44** is a quasi-transverse-electric mode, and curve **46** is a quasi-transverse-magnetic mode. The graph illustrates the exponential relationship between bend radius of curvature and bend loss.

To eliminate the loss associated with optical and optoelectronic integrated circuits as well as with waveguide bends, the present invention prevents light from propagating into the circuit substrate. Because the light cannot propagate into the substrate, it is confined within circuit and the waveguide.

In the preferred embodiment of the present invention, the substrate comprises a region which has a periodic dielectric structure. A periodic dielectric structure is a structure which exhibits a periodic spatial variation in dielectric constant. In one embodiment, the dielectric constant is periodic in two-dimensional space within the structure. In another embodiment, the structure exhibits three-dimensional spatial periodicity.

The periodic dielectric structure is characterized by a frequency or photonic band gap, or simply a band gap. The band gap of a periodic dielectric structure is a band of frequencies of electromagnetic radiation which cannot propagate through the structure in the plane in which the structure exhibits periodic variation in dielectric constant.

FIG. **4** is a schematic perspective view of a periodic dielectric structure **300** illustrating two-dimensional spatial periodicity. Specifically, the structure **300** is periodic in the x and z dimensions. Therefore, electromagnetic radiation having a frequency within the band gap of the structure cannot propagate in a plane parallel with the x-z plane, including the plane of the top surface **326** of the structure.

The structure **300** includes a plurality of elongated elements **322** extending orthogonal to the substrate top surface **326** and bottom surface **328**. The elements **322** are preferably cylindrically shaped and extend in a two-dimensional periodic arrangement relative to the x-z plane or any plane parallel thereto. Although cylindrical elements are described hereinafter, quasi-cylindrical elements or other shaped elongated elements may be employed. They may be formed of a non-conductive low-dielectric material disposed within a non-conductive high-dielectric substrate material **324**. The elements **322** may simply be bores, voids, or channels which may be filled with low-dielectric fluids or solids such as air and/or other liquid or solid material.

In an alternative embodiment, the elements may be formed of non-conductive high-dielectric material and may be disposed in the periodic arrangement in a non-conductive low dielectric material. An example of this configuration is a high-dielectric substrate with material etched away to leave only the periodic arrangement of cylindrical rods of the high-dielectric material with air in the spaces between the rods. The space may also be filled with some other low-dielectric fluid or solid.

A longitudinal axis **325** extends through the center of each element **322** in the vertical or y-direction. The elements **322** are arranged periodically in two dimensions in the x-z plane which is generally orthogonal to the longitudinal axes **325** extending through the elements **322**.

The structure **300** can be positioned to filter incoming electromagnetic energy **329** polarized in any direction that is propagating in the x-z plane. The structure **300** reflects substantially all of the incident electromagnetic energy **329** having a frequency within the range of the photonic or frequency band gap. More specifically, electromagnetic energy within the frequency range of the band gap is substantially prevented from propagating through the structure **300**. Thus, the structure **300** operates as a band stop filter. The structure maintains a substantially constant band gap frequency range for radiation propagating along any incident angle in the x-z plane.

FIG. **5**a is a top view of the structure **300** of FIG. **4**. In this embodiment, the cylindrical elements **322** are periodically arranged to provide a triangular lattice. The lines **327** illustrate the triangular lattice arrangement of the cylindrical elements along the top surface **326** of the substrate material **324**. Other possible lattice structures are shown in FIGS. **5b** and **5c**. FIG. **5b** shows a square lattice structure, and FIG. **5c** shows a honeycomb or hexagonal lattice structure.

A feature of the periodic dielectric structure is that the center frequency of the band gap, the bandwidth of the band gap (i.e., the stop band) and the band gap attenuation can be tailored for any frequency range in the microwave to ultraviolet bands (10^6 to 10^{15} Hz) during the fabrication of the structure. For the structure of FIGS. **4** and **5**, the center frequency (f), the bandwidth (Δf) and the band gap attenuation (A_G) of the band gap are shown in FIG. **6**. The attenuation (A_G) of the band gap is proportional to the number of rows of elements **322**. Thus, the attenuation (A_G) can be increased by providing additional rows. The center frequency (f) of the bandwidth (Δf) can be computed in accordance with the following equation:

$$f=[13.8(13/\mu\epsilon)^{1/2}]/a\ \text{GHz}$$

where

ϵ=dielectric constant of the substrate material,

μ=magnetic permeability of the substrate material, and

a=triangular lattice constant which corresponds to the distance in centimeters between centers of adjacent elements.

The location of the band gap on the frequency scale is determined by the center frequency. The bandwidth (Δf) is determined by the radius (r) of the cylindrical elements **322** and the triangular lattice constant (a).

A two-dimensional periodic dielectric structure as shown in FIGS. **4** and **5a–c** may be fabricated on a portion of a homogeneous or uniform substrate by one of several methods. One method involves drilling holes in a high-dielectric uniform substrate. The holes are filled with a low-dielectric material such as air.

Another method involves the use of reactive-ion etching. The substrate is covered on one face with a mask which contains a two-dimensional array of geometric figures of the size, spacing, and periodicity required for the desired band gap. This two-dimensional array of geometric figures may be patterned by employing electron beam lithography or conventional photolithography. The geometric figures are either transparent or opaque to a reactive-ion etchant used to selectively eradicate the high dielectric substrate material. For example, if cylindrical air channels are to be formed in the substrate, the geometric figures are circles which are transparent to the etchant, and the remainder of the mask is opaque to the etchant. If square rods of high dielectric material are to be formed, the figures are squares which are opaque to the etchant, and the remainder of the mask is transparent to the etchant.

The substrate and mask are then exposed to the highly directional reactive-ion etchant. The reactive-ion plasma is directed at the mask along the perpendicular axis, and vertical channels of the desired shape are created in the substrate. The resulting array of elements forms the two-dimensional frequency or photonic band gap.

FIG. **7a** is a schematic perspective view of an integrated optical circuit **200** in accordance with the present invention. FIG. **7b** is a top view of the circuit **200**. The circuit **200** comprises a base substrate **202** formed of a material having a low refractive index such as $Ga_xAl_{1-x}As$. An epilayer **204** made of a material having a higher refractive index than the base substrate **202** such as GaAs is formed on the top surface of the base substrate **202**. The combination of the base substrate **202** and the epilayer **204** forms the substrate **206** for the optical circuit **200**.

The components of the optical circuit **200** include two optical devices **208** and **210**. These devices may be a laser and a detector or other similar devices. It will be understood that the invention is applicable to other such devices. Also, two devices are selected for ease of description only. Typical circuits will have more devices.

The devices **208** and **210** are connected by a waveguide **212**. The waveguide **212** includes a straight section **214**, a bend **216** and a second straight section **218**. For illustration purposes, light is assumed to leave device **208** and propagate through the waveguide **212** toward device **210**. The light passes through straight section **214**, bend **216** and straight section **218** and enters device **210**.

The optical devices **208** and **210** are surrounded by periodic dielectric structure **222**. The periodic dielectric structure **222** prevents emissions from the devices **208** and **210** at a frequency within the band gap of the structure **222** from propagating into the substrate **206**. Thus, the devices **208** and **210** are isolated from each other, the waveguide **212**, and any other devices on the substrate **206**.

The periodic dielectric structure **222** also serves to define the lateral extents of the waveguide **212** on the epilayer **204**. The periodic dielectric structure **222** prevents light at a frequency within the band gap of the structure **222** from propagating in the plane of the epilayer **204**. Thus, the light is confined laterally within the waveguide **212**. Light is prevented from propagating out of the waveguide **212** in the vertical directions by internal reflection. Light will not propagate up out of the waveguide into space because of the refractive index contrast between the interior of the waveguide and the air above it. Light will not propagate down into the base substrate **202** because of the index contrast between the epilayer **204** and the base substrate **202**. Because the light cannot propagate outside the waveguide **212**, it is confined inside. The light entering the waveguide **212** from the device **208** travels through the straight section **214** into bend **216**. It is guided around the bend **216** by the periodic dielectric structure **222** and through straight section **218** into device **210**.

The circuit **200** of FIGS. **7a** and **7b** is made by first forming the uniform high-refractive-index epilayer **204** on top of a uniform low-refractive index base substrate **202** to form substrate **206**. This is done by diffusion or similar fabrication technique. Next, the devices **208** and **210** are formed on the epilayer **204**. Finally, the periodic dielectric structure **222** is formed in the substrate **206** by one of the methods previously described.

The periodic dielectric structure **222** is designed to create a frequency band gap for the substrate **206** which includes the frequency of the radiation which will be carried by the waveguide **212**. To create the structure **222**, the periodic pattern of holes is formed in the substrate **206**. The pattern of holes is made to surround devices **208** and **210** and to define the waveguide **212** connecting the devices. The holes are made by either drilling or by the reaction ion etching process previously described.

FIGS. **8a** and **8b** depict a section of waveguide **56** in accordance with another embodiment of the invention. A high-refractive-index epilayer **51** made of a material such as GaAs is formed on the top surface of a low-refractive-index base substrate **50** made of a material such as $Ga_xAl_{1-x}As$ to form a substrate **53**. The substrate **53** may also be made of other materials such as dielectric or optical materials. The periodic dielectric structure **52** is periodic in two dimensions in the plane of the epilayer **51**. The section of optical waveguide **56** is formed in the epilayer **51** between substantially parallel trenches **58** and **60**. The waveguide section **56** includes a 90° circular bend **62**. The 90° bend angle is chosen for illustration purposes only. The bend angle need not be 90°. The trenches **58** and **60** are formed by etching or other known processes. The air in the trenches provides refractive index contrast for internal reflection of the light carried by the waveguide **56**. Periodic dielectric structure **52** is provided outside the trenches **58** and **60** to eliminate loss where the requirements for total internal reflection are not met.

The periodic dielectric structure **52** is formed as described in connection with FIGS. **4–6** to have a frequency band gap at the known frequency of the light propagating in the waveguide **56**. Therefore, the light cannot propagate into the substrate **53** in the plane of the epilayer **51**. As a result, loss of light at the bend **62** is virtually eliminated.

To illustrate, light travels through the waveguide **56** in the direction of arrow **64**. As it enters the bend **62**, it strikes the barrier **66** between the waveguide **56** and trench **58** at increasing angles as described previously. In prior devices having a uniform substrate, the light would propagate into the substrate and be lost. However, in the present invention as shown in FIGS. **8***a* and **8***b*, the light cannot propagate into the substrate **53** because of the periodic dielectric structure **52**. Instead, the light is confined within the waveguide **56** and continues through the bend **62**.

In the embodiment of FIGS. **8***a* and **8***b*, the waveguide **56** is formed by creating the trenches **58** and **60** in the epilayer **51**. Other methods are also possible, including those previously described in connection with FIGS. **1***a* and **1***b*. A high-refractive-index channel may be formed by diffusing material into a uniform substrate or etching material onto the substrate. After the channel is formed, the periodic dielectric structure is formed in the substrate by the procedure previously described.

FIG. **9** illustrates a waveguide section **76** in accordance with another embodiment of the present invention. In this embodiment, the substrate **70** includes a high-refractive-index epilayer **71** and a lower-refractive-index base substrate **73**. The substrate **70** also comprises a periodic dielectric structure **72** having three-dimensional spatial periodicity. Radiation is prevented from propagating in all three spatial dimensions of the substrate **70**.

The three-dimensional periodic dielectric structure **72** is fabricated in a similar manner to the two-dimensional structure. The epilayer **71** is covered with a mask having a two-dimensional array of geometric figures defining the desired pattern for the top surface of the three-dimensional periodic dielectric structure. In one embodiment, the two-dimensional array has a triangular lattice pattern. The substrate and mask are exposed to the reactive-ion etchant. The etchant plasma is directed successively at three different angles with respect to the axis perpendicular to the top surface of the substrate. The angles are each oriented down 35.26° from the perpendicular and are separated by 120° from each other in azimuth. The resulting channels form a three-dimensional face-centered cubic lattice. The electromagnetic dispersion relation in this lattice will exhibit a photonic or frequency band gap.

With three-dimensional periodicity, the periodic dielectric structure **72** prevents propagation of light within the band gap in all three dimensions. Light cannot propagate laterally through the substrate **72** as in the two-dimensional case. But also, it cannot propagate toward the bottom surface **75** of the substrate **70**. Optical losses are further reduced.

FIGS. **10–12** illustrate various optical circuits to which the present invention is applicable. Each figure is a top view of a portion of a substrate on which is formed a device in accordance with the invention. The periodic dielectric structure used in each device may have either two-dimensional or three-dimensional periodicity.

FIG. **10** is a view of an S-bend device **93** in a waveguide section. The S-bend **93** is used in such devices as optical couplers. It includes two bend sections **90** and **91**. In prior devices with uniform substrates, these bends would be sources of radiation loss. However, because the bends are surrounded by a periodic dielectric structure **92** in the substrate **87**, the bend losses ae virtually eliminated.

FIG. **11** is a view of a Y-coupler device **103**. An incoming signal enters the device **103** through straight section **94**. The signal is split at junction **96** into two equal outgoing signals traveling through sections **98** and **99**. Radiation losses associated with the junction **96** and bends **100** and **101** are virtually eliminated by the periodic dielectric structure **102** in the substrate **97**. It should be noted that where radiation propagates from right to left in FIG. **11**, the device **103** serves a combiner.

FIG. **12** shows a waveguide taper or funnel **110** on a substrate **102** with a periodic dielectric structure **104**. Many applications require a fiber optic cable **112** to be permanently attached to a waveguide **114** on an optical integrated circuit. This connection can lead to insertion loss on the order of 10 dB. To reduce the loss, the cable end **116** of the integrated waveguide **114** is made the same width as the cable **112**. The optimum width of the circuit end **118** of the waveguide **114** is less than the width of the cable end **116**. The width transition between the two ends is made of a taper section **120**. This taper section **120** is a source of loss which can be overcome by the periodic dielectric structure **104**.

The present invention is not only applicable to optical systems. The periodic dielectric structure can be fabricated to have a frequency band gap anywhere in the microwave to ultraviolet bands (10^6 to 10^{15} Hz). Electromagnetic radiation at these frequencies can be prevented from propagating through a substrate. Therefore, the present invention is applicable to substantially confine radiation in waveguides, sources, detectors, lasers, power splitters, power combiners, tapers, interferometers, and any other device in which radiation needs to be confined. Losses can be substantially eliminated for electromagnetic radiation anywhere within the above frequency range.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

We claim:

1. A method of reducing radiation losses in optical integrated circuits, comprising:

providing a substrate;

forming the optical integrated circuit on or in the substrate; and

forming a region of said substrate with a periodic dielectric lattice structure having a spatially periodic variation in dielectric constant in at least two dimensions in which the lattice dimensions are proportioned to produce a frequency band gap defining a band of frequencies of electromagnetic radiation at which the optical integrated circuit is operable such that radiation at such frequencies is substantially prevented from propagating in at least one dimension within the region.

2. The method of claim 1 wherein the periodic dielectric lattice structure is formed at least partially within the optical integrated circuit.

3. The method of claim 1 wherein the step of forming the optical integrated circuit comprises forming a laser.

4. The method of claim 1 wherein the step of forming the optical integrated circuit comprises forming a detector.

5. The method of claim 1 wherein the step of forming the optical integrated circuit comprises forming a filter.

6. The method of claim 1 wherein the step of forming the optical integrated circuit comprises forming a modulator.

7. The method of claim 1 wherein the step of forming the optical integrated circuit comprises forming a power divider.

8. The method of claim 1 wherein the step of forming the optical integrated circuit comprises forming a power combiner.

9. The method of claim 1 wherein the step of forming the optical integrated circuit comprises forming a switch.

10. The method of claim 1 wherein the periodic dielectric lattice structure is formed periodic in two dimensions.

11. The method of claim 1 wherein the periodic dielectric lattice structure is formed periodic in three dimensions.

12. The method of claim 1 wherein the step of providing a substrate comprises providing a semiconductor material.

13. The method of claim 1 wherein the step of forming a region comprises forming a periodic pattern of void regions in the substrate.

14. A method of reducing radiation losses associated with optical waveguides, comprising:

providing a substrate;

forming an optical waveguide on or in the substrate; and

forming a region of said substrate with a periodic dielectric lattice structure having a spatially periodic variation in dielectric constant in at least two dimensions in which the lattice dimensions are proportioned to produce a frequency band gap defining a band of frequencies of electromagnetic radiation at which the optical waveguide is operable such that radiation at such frequencies is substantially prevented from propagating in at least one dimension within the region, said region being proximate to said waveguide.

15. The method of claim 14 wherein the waveguide is formed with a bend.

16. The method of claim 14 wherein the waveguide is formed with a taper.

17. The method of claim 14 wherein the periodic dielectric lattice structure is formed periodic in two dimensions.

18. The method of claim 14 wherein the periodic dielectric lattice structure is formed periodic in three dimensions.

19. The method of claim 14 wherein the step of providing a substrate comprises providing a semiconductor material.

20. The method of claim 14 wherein the step of forming a region comprises forming a periodic pattern of void regions in the substrate.

21. The method of claim 14 wherein the step of forming an optical waveguide comprises preventing the region with the periodic dielectric lattice structure from being formed in a specific portion of the substrate, said specific portion of the substrate being the optical waveguide.

22. The method of claim 14 wherein the step of forming an optical waveguide comprises diffusing a material into the substrate, said material having an index of refraction higher than the index of refraction of the substrate.

23. The method of claim 14 wherein the step of forming an optical waveguide comprises depositing a material onto a surface of the substrate, said material having a higher index of refraction than the index of refraction of the substrate.

24. The method of claim 14 wherein the step of forming an optical waveguide comprises forming two substantially parallel trenches in a surface of the substrate, said trenches defining a channel of material between them, said channel of material being the optical waveguide.

25. An optical circuit, comprising:

a substrate having a region with a periodic dielectric lattice structure having a spatially periodic variation in dielectric constant in at least two dimensions in which the lattice dimensions are proportioned to produce a frequency band gap defining a band of frequencies of electromagnetic radiation at which the optical circuit is operable such that radiation at such frequencies is substantially prevented from propagating in at least one dimension within the region; and

at least one optical device formed on or in the substrate proximate to the region with the periodic dielectric lattice structure, such that radiation from the optical device having a frequency within the frequency band gap is substantially prevented from propagating within the substrate.

26. The optical circuit of claim 25 wherein the periodic dielectric lattice structure is formed at least partially within the optical device.

27. The optical circuit of claim 25 wherein the optical device is a laser.

28. The optical circuit of claim 25 wherein the optical device is a detector.

29. The optical circuit of claim 25 wherein the optical device is a filter.

30. The optical circuit of claim 25 wherein the optical device is a modulator.

31. The optical circuit of claim 25 wherein the optical device is a power divider.

32. The optical circuit of claim 25 wherein the optical device is a power combiner.

33. The optical circuit of claim 25 wherein the optical device is a switch.

34. The optical circuit of claim 25 wherein the periodic dielectric lattice structure is periodic in two dimensions.

35. The optical circuit of claim 25 wherein the periodic dielectric lattice structure is periodic in three dimensions.

36. The optical circuit of claim 25 wherein the substrate comprises a semiconductor material.

37. The optical circuit of claim 25 wherein the region with the frequency band gap comprises a periodic pattern of void regions in the substrate.

38. An optical circuit, comprising:

a substrate having a region with a periodic dielectric lattice structure having a spatially periodic variation in dielectric constant in at least two dimensions in which the lattice dimensions are proportioned to produce a frequency band gap defining a band of frequencies of electromagnetic radiation at which the optical circuit is operable such that radiation at such frequencies is substantially prevented from propagating in at least one dimension within the region; and

at least one optical waveguide formed on or in the substrate proximate to the region with the periodic dielectric lattice structure, such that radiation in the waveguide at a frequency within the frequency band gap is substantially prevented from propagating into the substrate.

39. The optical circuit of claim 38 wherein the optical waveguide comprises a bend.

40. The optical circuit of claim 38 wherein the optical waveguide comprises a taper.

41. The optical circuit of claim 38 wherein the periodic dielectric lattice structure is periodic in two dimensions.

42. The optical circuit of claim 38 wherein the periodic dielectric lattice structure is periodic in three dimensions.

43. The optical circuit of claim 38 wherein the substrate comprises a semiconductor material.

44. The optical circuit of claim 38 wherein the region with the frequency band gap comprises a periodic pattern of void regions in the substrate.

45. The optical circuit of claim 38 wherein the optical waveguide is a channel in the substrate surrounded by the periodic dielectric lattice structure.

46. The optical circuit of claim 38 wherein the optical waveguide is a channel of material diffused into the substrate, said material having an index of refraction which is higher than the index of refraction of the substrate.

47. The optical circuit of claim 38 wherein the optical waveguide is a channel of material deposited on a surface of the substrate, said material having an index of refraction which is higher than the index of refraction of the substrate.

48. The optical circuit of claim 38 wherein the optical waveguide is a channel of material between two substantially parallel trenches in a surface of the substrate.

49. The method of claim 1 wherein the region with the periodic dielectric lattice structure is formed proximate to the optical integrated circuit.

50. The method of claim 1 wherein the region with the periodic dielectric lattice structure is formed within the optical integrated circuit.

51. The optical circuit of claim 25 wherein the region with the periodic dielectric lattice structure is proximate to the optical device.

52. The optical circuit of claim 25 wherein the region with the periodic dielectric lattice structure is within the optical device.

53. The method of claim 1 wherein the step of forming a region comprises forming a periodic pattern of holes in the substrate to form a periodic pattern of elements of a dielectric constant different from the dielectric constant of the substrate.

54. The method of claim 53 wherein the periodic pattern of elements formed is periodic in two dimensions.

55. The method of claim 53 wherein the periodic pattern of elements formed is periodic in three dimensions.

56. The method of claim 53 wherein the step of forming a periodic pattern of holes comprises drilling.

57. The method of claim 53 wherein the step of forming a periodic pattern of holes comprises reactive ion etching.

58. The method of claim 14 wherein the step of forming a region comprises forming a periodic pattern of holes in the substrate to form a periodic pattern of elements of a dielectric constant different from the dielectric constant of the substrate.

59. The method of claim 58 wherein the periodic pattern of elements formed is periodic in two dimensions.

60. The method of claim 58 wherein the periodic pattern of elements formed is periodic in three dimensions.

61. The method of claim 58 wherein the step of forming a periodic pattern of holes comprises drilling.

62. The method of claim 58 wherein the step of forming a periodic pattern of holes comprises reactive ion etching.

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